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UCRL-50163 Part I

PREDICTION OF THE MAXIMUM DOSAGE TO MAN FROM THE FALLOUT OF NUCLEAR DEVICES

I. ESTIMATION OF THE MAXIMUM CONTAMINATION OF AGRICULTURAL LAND

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PREFACE

The extensive coverage given to I^{131} and infant thyroid dosages subsequent to nuclear device testing at the Nevada Test Site is sufficient evidence to indicate that both preshot prediction and postshot documentation of the dosage to humans from internal emitters was inadequate. So far as I^{131} is concerned, the postshot documentation was partially corrected in 1957. However, this documentation capability was not integrated with preshot prediction and as a result "surprises" occurred following the July 1962 tests.

Whether or not such "surprises" could have been anticipated in July 1962 is at this time academic. It is important to point out, however, that there is every reason to believe that these "surprises" need not occur in future events if an adequate program of preshot prediction is integrated with an adequate program of postshot documentation. Off-site radiological safety programs should and can be conducted with the same degree of planning and precision as laboratory experiments. Thus, preshot prediction should not serve the sole purpose of preshot rad-safe analysis. Rather, it should also have the function of guiding the postshot documentation by suggesting what to measure, where to measure it, and the precision required in the measurement. Furthermore, the preshot prediction program should feed on the postshot documentation results in order to improve subsequent predictions.

There are two other points that appear to be obvious conclusions from previous test results: 1) No radionuclide that is produced should be ignored until a critical analysis demonstrates that it is insignificant, and 2) preshot prediction and preshot documentation must encompass distances extending 2000 to 3000 miles from the site of detonation.

The Information Integration Group of the Bio-Medical Research Division has accepted the responsibility for developing this preshot predictive capability. UCRL-50163 (Parts I and II) presents our approach to predicting the dosage from each and every radionuclide that is released to the atmosphere and deposited on agricultural lands remote from the site of detonation. Our group is also investigating the aquatic transport of nuclear debris by surface and ground water into fresh water and marine ecosystems; this will be presented in a separate report.

In Part I of this report the approach that we shall use to estimate the fallout and rainout levels as a function of cloud travel time for periods up to 50 hr post detonation is presented. Part II, "Estimation of the Maximum Dose from Internal Emitters," by Yook C. Ng and Stanley E. Thompson, will show how these fallout estimates can be combined with radionuclide production estimates and biological uptake relationships to arrive at burden and dosage estimates for man.

There were three questions which we could have asked concerning the outcome of the detonation of a nuclear device. Therefore, it is essential that the reader recognize which of the three is the question that we are trying to answer and why we feel that it is the most appropriate question to answer. The three questions which we could have asked are:

(1) What is the worst situation that could develop?

(2) What is the most likely situation that will develop?

(3) What would be the situation if everything went off perfectly?

We choose to answer the first question and to direct our efforts toward predicting the worst case. (However, in the process of answering the first question we can generally answer the second. Quite obviously, the answer to the third question has no meaning with respect to public health and safety.) We feel that only the worst case should be compared with prescribed tolerances in a preshot rad-safe analysis. Moreover, it is only when we know the worst case that we can establish an adequate system of postshot monitoring to document the actual case and to insure that appropriate countermeasures are instituted when and if needed. In other words, it is only by this approach that uncertainties concerning dosimetry, such as presently exist in the case of I^{131}, can be eliminated.

Furthermore, we are attempting to be quite thorough in our analyses and are considering each and every radionuclide recorded on the chart of the nuclides. In this respect, our estimates may indicate that a particular radionuclide is a hazard for one of two reasons: 1) Either it will be a hazard because of what we know about it or 2) it will be a hazard because of what we don't know about it. If a pertinent relationship is not known concerning a particular radionuclide, we make worst case estimates of the relationship and, hence, maximize our estimates of hazard. Nevertheless, even though it is conservative, this approach still allows us to eliminate most of the radionuclides from consideration and to indicate those that are potentially the most hazardous. Obviously, it also allows us to estimate the upper limit of the potential burden and dosage; however, due to the perversity of nature, the precise dosage can only be determined by postshot documentation in the affected areas.

It is obvious that had I^{131} been measured in milk during the early period of testing, its dosimetry would not be a problem. Thus, through our predictive approach we want to be able to indicate what should be measured, where it should be measured, and with what precision it should be measured. There would appear to be no other way to assure that the dosimetry of future events is unambiguous and that the need for countermeasures is recognized in time so that they can be planned for and instituted when and if needed. In this respect, the most appropriate countermeasures lie in device design. In Part II of this report, by Ng and Thompson, it is shown how this predictive approach can supply guide lines for the design of nuclear devices that might be used in the construction of a sea level canal.

Thus, this predictive approach is meant to serve three purposes:

1) First, in preshot rad-safe analysis, by determining whether or not a particular event can be conducted without exceeding existing tolerances.
2) Second, in guidance for postshot documentation, by indicating what should be measured, where it should be measured, and with what precision it should be measured.
3) Third, in guidance for device design, by indicating the maximum amount of a radionuclide that can be produced and subsequently released to the environment without exceeding prescribed tolerances.

PREDICTION OF THE MAXIMUM DOSAGE TO MAN FROM THE FALLOUT OF NUCLEAR DEVICES

I. ESTIMATION OF THE MAXIMUM CONTAMINATION OF AGRICULTURAL LAND

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ABSTRACT

Part I of this report presents a semi-empirical approach toward estimating the maximum contamination of agricultural land by radionuclides produced by nuclear devices. It is based upon the maximum fallout levels observed subsequent to all previous tests of nuclear devices and applies to cloud travel times or fallout arrival times ranging from 1 to 50 hr and beyond.

INTRODUCTION

While considerable effort has been directed toward fallout prediction models and while considerable is known about the transport of fallout particles in, and the deposition of these particles from, the atmosphere, fallout models are reasonably successful only in predicting the relatively close-in fallout of large particles ($>20\ \mu$ in diam). The major reason for this is that predicting long-range fallout is tantamount to predicting the weather. It requires prediction of the velocity and direction of wind and the amount of rainfall 50 or more hours in advance over distances of 2000 or more miles. At the same time, the iodine problem arising from previous tests of nuclear explosive devices indicates that just such an ability is required in order to make an adequate preshot rad-safe analysis of any future tests that might release radioactivity to the atmosphere, such as the Plowshare Program for the peaceful uses of nuclear explosive devices.

The purpose of Part I of this document is to present a semi-empirical approach to the prediction of long-range fallout of tropospheric debris from Plowshare cratering experiments. It is based upon observed fallout levels that have occurred subsequent

to previous nuclear device tests. The approach is directed toward predicting the maximum credible fallout level that could contaminate agricultural lands remote from the detonation site. The maximum credible level is the most significant level from the standpoint of public health and safety. Thus, this report is not intended to be a sophisticated treatise on meteorology. It is not directed toward the prediction of likely fallout levels given a certain set of input parameters; rather, it presents the approach that is used by the Bio-Medical Research Division to estimate what might be the worst case for some suggested nuclear event.

Previous experiments concerning cratering with nuclear explosive devices have shown that there are two types of clouds produced in a cratering event: a main cloud, similar to the one produced by a tower shot, that separates from the ground and rises to some height, and a base-surge cloud that hugs the ground and extends upward depending upon the yield of the device. Except for very-low-yield shots (<1 kt), the height of the base-surge cloud is such that the treatment used in this report can be applied to both clouds.

In predicting the maximum dry fallout or wet deposition, we have applied the experience gained from tower detonations. Because of the lack of sufficient data, worst-case assumptions have been made concerning activity versus particle-size distribution and concerning the fraction of the activity released to the atmosphere.

ATMOSPHERIC DIFFUSION COEFFICIENTS

As a nuclear cloud moves downwind from the site of detonation, its concentration is reduced by horizontal and vertical eddy diffusion as well as by velocity and directional wind shear. The effects of shear are discussed in the subsequent section of this report. It suffices here to state that maximum dry fallout or wet deposition occurs in the absence of shear.

In estimating dispersion of material in the atmosphere over large distances or over long travel times, a Fickian-type diffusion is assumed. As a result, the standard deviation of the spread of the material is given by

$$\sigma_h = \sqrt{2K_h t}$$

and

$$\sigma_v = \sqrt{2K_v t} \quad ,$$

where K_h is the horizontal eddy-diffusion coefficient and K_v is the vertical eddy-diffusion coefficient. In the following treatment, a numerical value for K_v is not required.

Heffter has reviewed all the previous data relative to K_h and has determined that for long travel times (>24 hr) an average value of $K_h = 4 \times 10^4$ m^2/sec will fit most of the data.[1] At the same time, the data he presents support the concept of accelerated relative diffusion as put forth by Pasquill.[2] This concept suggests that the value of K_h increases with cloud travel time. The explanation for this is that as the cloud grows in size, it is influenced by larger and larger eddies and hence the apparent value of K_h increases. In the following treatment, we shall use a value of $K_h = 4 \times 10^3$ m^2/sec at a travel time of 1 hr and increase this to 4×10^4 m^2/sec at a travel time of 24 hr. Both values of K_h are consistent with the data presented by Heffter, and the lower value compares with the value 6×10^3 m^2/sec used by Knox in the prediction of close-in fallout.[3]

ESTIMATED MAXIMUM WET DEPOSITION

There are two processes of wet deposition: washout and rainout. Washout refers to the process where the raindrops fall through the debris cloud and remove the particles from the cloud by impaction. In rainout, the radioactive particles actually enter the cloud during the rain-formation process and act as condensation nuclei for the raindrops.

The magnitude of a washout depends upon the fraction of the activity below the rain-producing layer, the horizontal dimensions of the radioactive cloud when the rain begins, and the rainfall rate. Maximum washout occurs when all of the activity is below a rain-producing layer with a high rainfall rate. If the above values of K_h are used and the nominal radius of the cloud is assumed to be two standard deviations, the horizontal area of the cloud (A_h) is given by

$$A_h = 3.6 \times 10^8 \text{ at 1 hr}$$

and by

$$A_h = 3.6 \times 10^9 t \text{ at} > 24 \text{ hr},$$

where A_h is expressed in meters squared and t is expressed in hours. In the absence of velocity or directional wind shear, A_h is the area of the cloud projected onto the earth's surface. Hence, the maximum fractional washout is given by $1/A_h$ providing that all of the cloud is below the rain-producing layer during a period of high rainfall rate.

The situation is somewhat different with respect to rainout, especially for thunderstorms. In a thunderstorm, a developing cumulus cell is characterized by updrafts that draw the air in from below. It is by this process that the radioactive particles are carried into the rain-producing region. The entire life of such a cell is of the order of an hour; its mature stage, during which precipitation occurs, may last for 15 or 20 min. A large, persistent storm may develop successive cells in turn. Thus, a storm can contain a number of cells in different stages of development.

These individual cells have horizontal dimensions ranging from 1 to 5 miles. However, as they are in the process of developing, they may engulf air and, hence, radioactive debris from a larger area. In other words, a thunderstorm can reconcentrate the debris before it is rained out and thus lead to higher localized fallout levels than the washout process. At the same time, the wet deposition by both processes should be related to the horizontal area of the cloud.

Thus, in the case of rainout the average deposition is still given by $1/A_h$; however, within the overall rainout area, localized areas may receive depositions that are higher than this. This will be discussed again, subsequently.

Figure 1 presents the rain-deposition data collected by the gummed-film network following previous tower shots at the Nevada Test Site. These data are plotted as fractional rain deposition versus post-detonation time and are corrected for decay.* (To apply the data to a particular radionuclide, they must be corrected for its decay.) The curve of $1/A_h$ versus t is shown (labeled 1/t); it can be seen that essentially all of the measured values are a factor of 10 or more lower than the predicted value except for the single point at 42 hr. This point represents a rainout that occurred in Fargo, North Dakota, following the Diablo Event of the Plumbbob series. The calculated postshot wind trajectories suggest that there was probably little wind shear in the main body of the Diablo cloud and that the rainfall was intense. At the same time, the wind-trajectory data indicate that there was considerable wind shear associated with the next highest points recorded at 36 and 42 hr. The remainder of the points are associated with shear and/or lower rainfall rates.

In keeping with the above approach, the effect of wind shear is to increase the projected area of the cloud on the earth's surface. In the simplest case, it changes the shape of the area from a circle to a rectangle with rounded ends. The width of the rectangle is determined by horizontal eddy diffusion and the length by the wind-velocity shear. This suggests that, to account for shear, A_h should be given by $A_h = 3.6 \times 10^9 t^n$, where n is some value greater than unity. Also shown in Fig. 1 is the curve of the above relationship with n = 1.7. As can be seen, this curve intersects the next highest group of points.

*The basic data and the details of the calculations leading to the points in Fig. 1 are given in the Appendix.

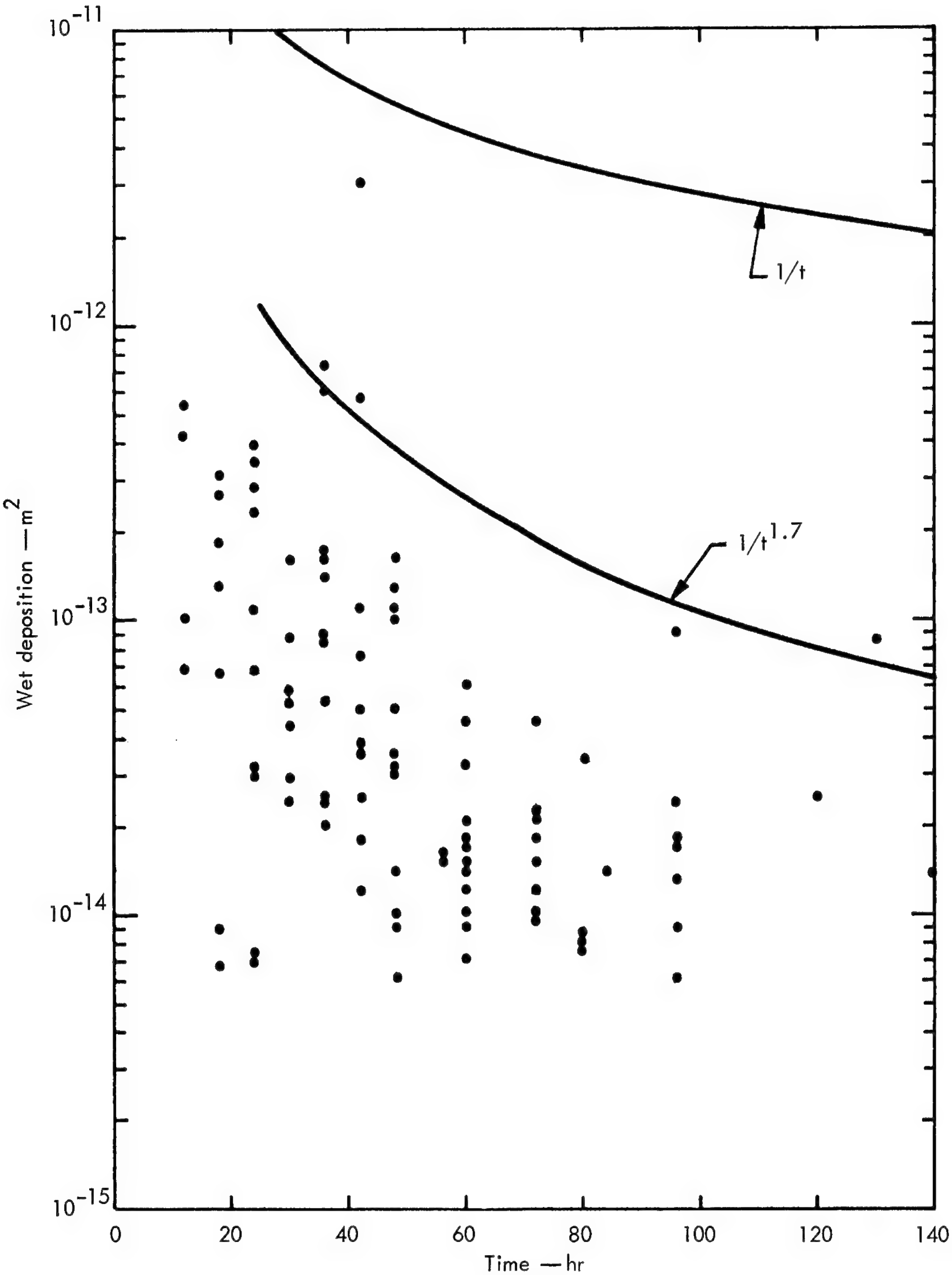

Fig. 1. Fractional rain deposition versus post-detonation time (corrected for decay).

Since we are concerned here with predicting the maximum credible rainout rather than the most probable rainout, inspection of Fig. 1 indicates that we must make a choice between the $1/t$ curve, the $1/t^{1.7}$ curve, or some combination of the two. It appears reasonable to assume that the longer the travel time, the greater the probability that the cloud is influenced by significant wind shear. In fact, these data would suggest that even for travel times of 24 to 48 hr, significant shear effect is the rule with the exception of the Fargo rainout. Yet, the Fargo case must be considered as representative of a credible situation, and from the standpoint of public health and safety, the $1/t$ relationship should be used to predict the maximum credible wet deposition, at least over the first 50 hr of travel time. Since a cloud can travel 1000 or more miles away from the site of detonation in 50 hr, pastures which supply milk to large off-site populations could be affected by heavy rainout within this time period. In other words, the maximum credible wet deposition must be shown to be acceptable at earlier travel times (<50 hr), and as the Fargo case indicates, this requires use of the $1/t$ relationship. One other consideration which suggests that the $1/t$ relationship should be used is the localized hot spots that may develop within a rainout area. Indeed, it is unlikely that the gummed-film samplers at Fargo recorded the highest-intensity rainout in that occurrence. The same consideration would apply to any of the other samplers.

If the fractional wet-deposition levels read from the $1/t$ curve are called R, then the estimated maximum wet deposition (R_i) of any radionuclide (i) is given by the equation

$$R_i = P_i T_i R e^{-\lambda_i t},$$

where P_i is the curies of radionuclide produced, T_i is the total fraction of radionuclide released to the atmosphere, and λ_i is the radiological decay rate of the isotope.

ESTIMATED MAXIMUM DRY FALLOUT

A considerable amount of effort has been applied to the construction and testing of fallout models capable of predicting the close-in dry fallout from nuclear explosive devices. The models have been quite successful in predicting this close-in dry fallout.[4,5] However, they are only applicable to the fallout of larger particles (>20 μ in diam).

In Fig. 2, the observed fractional dry fallout levels (F) from previous tower detonations at the Nevada Test Site are plotted as a function of time. Also, a line is drawn in the figure that includes all of the highest observed fractional dry fallout. This line is given by the equation $F = 10^{-11} e^{-0.01t}$. Thus in accord with

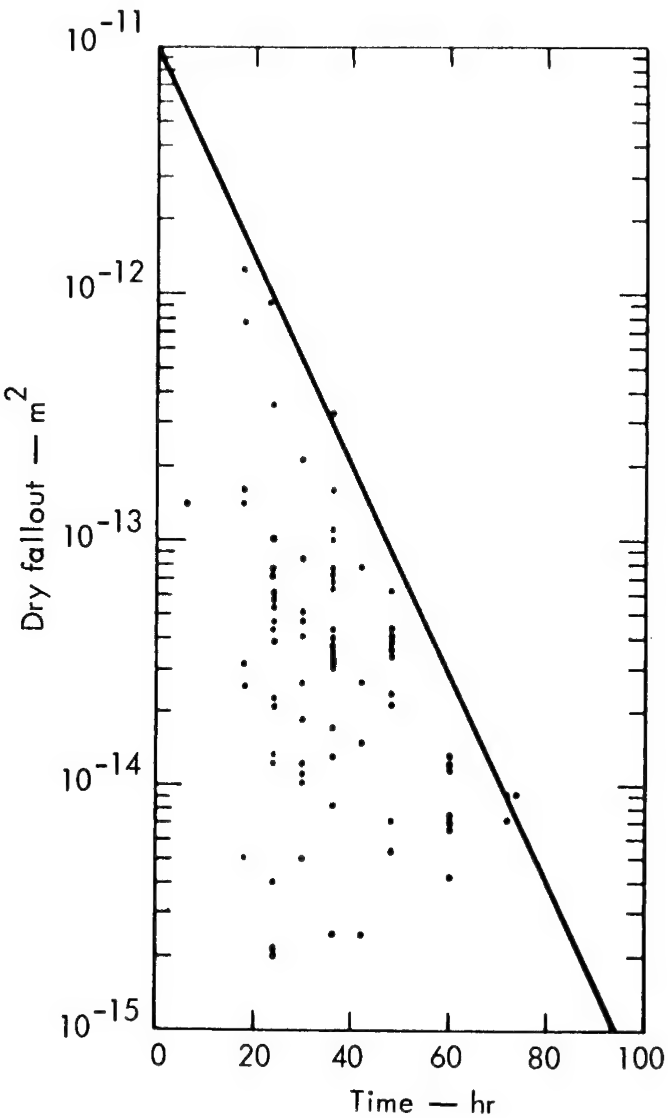

Fig. 2. Fractional dry fallout versus post-detonation time (corrected for decay).

the data presented in Fig. 2, we suggest that the following equation be used to predict the maximum fallout (F_i) of any radionuclide (i) from the main cloud of a cratering experiment:

$$F_i = P_i T_i F e^{-\lambda_i t},$$

where P_i is the curies of radionuclide produced, T_i is the fraction of radionuclide produced that is injected into the main cloud, and λ_i is the radiological decay rate of the isotope.

FRACTION RELEASED TO THE ATMOSPHERE

The predictive relationships presented in the previous section apply to the activity that is released to the atmosphere at the site of detonation. All of the activity produced is released to the atmosphere when a device is detonated on a tower, but only a fraction of the activity is released when the device is detonated underground. In the extreme case, when the device is buried at an appropriate depth, all of the activity remains underground. In cratering experiments where the expanding cavity ruptures the surface to form the crater, the material above the device acts like a filter bed and removes a large portion of the radioactive material that would otherwise be released to the atmosphere. The efficiency with which a radionuclide is removed depends upon its chemical and physical properties or those of its precursors during the venting process. Therefore, fission products such as Cs^{137} and Sr^{89}, which are present as their rare-gas precursor during the venting process, are found in much higher relative concentrations in the cloud than a refractory radionuclide such as Zr^{95} or Nd^{147}. Therefore, to the extent possible, the fraction released to the atmosphere should be determined for each specific radionuclide of interest.

As with tower shots, the fallout models that have been applied to cratering shots are concerned only with the close-in fallout of the larger particles. The activity versus particle-size distributions that are used have been adjusted to fit the fallout fields observed subsequent to the test. In the case of tower shots, this distribution accounts for only one-third of the total airborne activity. The other two-thirds is associated with the neglected fraction contained in smaller particles. Following the Sedan experiment, the close-in fallout pattern corresponded to the predicted pattern when the fraction of the activity released to the atmosphere was assumed to be 10%; following Danny Boy, this correspondence occurred at an assumed release of 5%.[5] If we assume a correspondence to tower shots, this would suggest that 20% and 10% were released on smaller particles, leading to a total release of 30% and 15%. However, the assumption of correspondence between tower and cratering shots does not appear to be justified, particularly for Danny Boy. A smaller fraction would appear to be released on the small particles when one examines the data for individual isotopes.

Table I presents the relative fraction (relative to Sr^{89}) of a number of radionuclides present in close-in fallout samples and in a late-time (138 min) cloud sample following the Danny Boy test.[6]

Table I. Relative fraction of nuclides present following the Danny Boy test.

Radionuclide	Fraction relative to Sr^{89} Fallout	Cloud
Sr^{89}	1.0	1.0
Sr^{90}	1.2	0.6
Zr^{95}	0.2	0.003
Ag^{111}	-	0.008
Cd^{115}	-	0.01
Cs^{136}	0.6	0.008
Cs^{137}	1.1	1.0
Ba^{140}	0.8	0.2
Ce^{141}	0.6	0.005
Eu^{156}	0.2	0.002

If this debris were unfractionated, all of the relative fractions would be equal to unity. This is substantially the case for the larger particles that comprise the close-in fallout, except for the refractory radionuclides of zirconium and europium. However, the cloud sample is highly fractionated. Since this is a late-time cloud sample, it should reflect the activity on the smaller particles. If we assume that all of the Sr^{89} produced is present on the smaller particles, the cloud data suggest that, except for Sr^{90}, Cs^{137}, and Ba^{140}, which have rare-gas precursors, only 1% or less of the other radionuclides appeared on the smaller particles. Actually, Miskel estimates that only some 13% of the Cs^{137} or Sr^{89} was present in the cloud,[6] and this suggests that the others were present at only 0.1%.

At this time we have no comparable data on the Sedan cloud. However, ground-level air and fallout samples were collected in the Midwest one and two days subsequent to the Sedan test.[7] The results of these analyses are shown in Table II.

The data show that the air samples were quite comparable to the fallout samples, in sharp contrast to the Danny Boy data. In this case, if we assume that all of the Sr^{89} were released, these data would suggest that some 20% of the activity was released on smaller particles.

Table II. Relative fractions of nuclides present following the Sedan test.

Radionuclide	Fraction relative to Sr^{89} Fallout	Cloud
Sr^{89}	1.0	1.0
Sr^{90}	0.7	0.4
Y^{91}	0.12	0.07
Ru^{103}	0.08	0.05
Ru^{106}	0.25	0.12
Cs^{137}	1.9	1.45
Ba^{140}	0.2	0.15
Ce^{141}	0.12	-
Ce^{144}	0.16	-

There are reasons to believe that the released fractions from the Sedan test were different from the Danny Boy test. One reason is the difference in yield: 100 kt for Sedan and 0.42 kt for Danny Boy. The other is that Sedan was conducted in a water-saturated medium, whereas Danny Boy was conducted in a dry medium. Both of these reasons probably contributed to the factor-of-2 difference found in the fraction of the activity observed on larger particles: 10% for Sedan and 5% for Danny Boy. Furthermore, the presence of water

in the expanding cavity could change the nature of the chemical species present at the time of cavity rupture and venting. Relatively non-volatile oxides could be replaced by volatile hydroxides during the venting process.

Until more data become available with respect to the fraction of the activity released to the atmosphere on small particles as a function of yield and medium, it is necessary to use worst-case assumptions. Therefore, until these additional data are available, we shall assume that an amount of radioactivity equal to that observed on larger particles is released to the atmosphere on smaller particles. We shall also assume that as the yield increases in the dry medium, the vented fraction will also increase. The values shown in Table III are thus assumed.

Table III. Assumed values of the fraction of the activity released to the atmosphere.

Isotope	T_i [a]	S_i [b]
Sr^{89}, Cs^{137}	1.0	1.0
Sr^{90}, Y^{91}, Ba^{140}	0.5	0.5
All others	0.2	0.1

[a] Total activity released.

[b] Activity on small particles.

The available data suggest that these values may overestimate the fraction on smaller particles by a factor of 10. We offer no other justification for these values at this time, except that they represent conservative estimates. The reader should anticipate that as more data become available, these estimates may be revised.

ESTIMATED MAXIMUM CONTAMINATION

If the estimates of the vented fractions are combined with the fractional dry-fallout and wet-deposition relationships, the following relationships are obtained:

$$R_i = P_i R_i' e^{-\lambda_i t}$$

and

$$F_i = P_i F_i' e^{-\lambda_i t} ,$$

where $R_i' = T_i R$

and

$$F_i' = T_i F .$$

These primed values are shown in Table IV for the group with $S_i = 0.1$ and $T_i = 0.2$; that is, the group with no rare-gas precursors.

Table IV. Values of R_i' and F_i' for the group with no rare-gas precursors.

Time (hr)	R_i'	F_i'
1	6×10^{-10}	2×10^{-12}
6	4×10^{-11}	1×10^{-12}
12	9×10^{-12}	6×10^{-13}
24	2×10^{-12}	2×10^{-13}
48	1×10^{-12}	2×10^{-14}

For most radionuclides of interest, the decay correction can be ignored and these primed values can be multiplied by the curies produced (P_i) to obtain the estimated maximum dry fallout or wet deposition.

In 12 hr a debris cloud could travel 100 to 200 miles and, hence, be beyond what might be considered a close-in controlled area. At 12 hr the cloud diameter (assuming it is 4σ) would be 100 miles. Thus, these values suggest that if wet deposition occurred at 12 hr, a large area (about 8000 miles^2) could receive the following estimated maximum fractional contamination (EMC):

EMC (12 hr) = 5×10^{-11} (Sr^{89}, Cs^{137}),

EMC (12 hr) = 2.5×10^{-11} (Sr^{90}, Y^{91}, Ba^{140}), and

EMC (12 hr) = 10^{-11} (all others).

These EMC values are used for illustrative purposes in Part II of this report. As the R_i' values indicate, maximum contamination levels higher than these can occur by wet deposition at times earlier than 12 hr. Obviously, in any actual case the more appropriate higher values should be applied for cloud travel times of less than 12 hr.

The data plotted in Fig. 1 indicate that a wet deposition comparable to the levels representative of the EMC values above occurred only once subsequent to some 100 tests conducted at the Nevada Test Site, and that the next most likely situation resulted in contamination levels that were a factor of 10 lower. It therefore appears reasonable that these EMC values should be reduced by a factor of 10 when considering the composite of a series of events, such as those proposed for the construction of a sea-level canal. The basis for this is that it is unlikely that several events would each lead to the maximum contamination of the same area. Thus, we propose to use the above values for any single event and to use values of a factor of 10 lower for the composite of a series of events.

* * * * *

In Part II of this report, "Estimation of the Maximum Dose from Internal Emitters," the above EMC values are used together with isotope-production estimates and biological-uptake factors to arrive at burden and dosage estimates for man. The discussion section of Part II also gives suggested guidelines for applying this overall predictive approach to specific events.

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APPENDIX
HISTORICAL FALLOUT DATA

Basic Data

The fallout data used in this report are the results of the gummed-film monitoring network of the Health and Safety Laboratory.[A1-A3]

Tables A-I and A-II (following p. 15) present the data abstracted from the reported results of the gummed-film network. These tables are arranged chronologically by test shot and present the gross beta activity, in $\mu Ci/m^2/day$, of the fallout collected on the gummed film at the various sampling stations. List indicates that the values reported for the Tumbler-Snapper Events should be increased by a factor of 3 (except for the very high values).[A2] This correction was the result of recalibration of their automatic counting equipment. The authors stated that the higher samples were not counted on the automatic equipment. The values below 5 $\mu Ci/m^2/day$ were, therefore, increased by this factor. Also recorded in Tables A-I and A-II are the cloud arrival times and the altitude of the cloud trajectory calculated to have passed over the sampling station. The time of fallout (cloud arrival time) was estimated from the sampling date and/or the calculated trajectory as given in the references. The tables also indicate whether the fallout occurred by wet or dry deposition.

The values recorded in Table A-I were originally given as $dpm/ft^2/day$, extrapolated to the sampling day. These were converted to $\mu Ci/m^2/day$ as recorded in the table. The data for the Teapot Series, Table A-II, were reported as $\mu Ci/100\ miles^2/day$ extrapolated to January 1, 1956, by using the $T^{-1.2}$ relationship. These values were extrapolated back to the sampling date and converted to $\mu Ci/m^2/day$ as recorded in the table. Only values in excess of 0.5 $\mu Ci/m^2/day$ were abstracted and recorded in Tables A-I and A-II. In the absence of a recent test shot, the fallout recorded at a sampling station was at least below 0.05 $\mu Ci/m^2/day$ and usually below 0.005 $\mu Ci/m^2/day$. Consequently, there is little doubt that a value in excess of 0.5 $\mu Ci/m^2/day$ can be assigned to a recent test shot.

Conversion to Fractional Dry Fallout or Wet Deposition

The data recorded in Tables A-I and A-II were first normalized to a yield of 1 kt by dividing the values recorded for each test shot by the yield of the test shot. These

normalized values were then divided by the total beta activity per kiloton of fission corrected for decay to the sampling date. In this analysis it was assumed, for ease of calculation, that at H + 24 hr the total beta activity per kiloton was 10^{13} μCi. (This is some 20% less than the theoretical value.)

Correction for Gummed-Film Efficiency

Comparison of gummed-film results with those of pot collectors has shown that the pot values are, on the average, a factor of 1.6 higher; this correction is applied to the gummed-film data when making Sr^{90} estimates.[A4] Since the dry deposition velocity has been determined to be identical between the two types of samplers,[A5-A7] this factor is due to their different efficiencies in the collection of fallout occurring in rain and should be applied only to fallout in rain. This factor undoubtedly results from the activity being washed off the gummed-film during rain, whereas the pots are absolute collectors. This correction factor has been applied to the data in Tables A-I and A-II only for the fallout that occurred in rain.

Fargo, North Dakota

The highest fractional rainout value recorded in Fig. 1 at 42 hr was derived from an estimate of the Sr^{90} deposition.[A8] A deposition of 22 mCi/mi^2 of Sr^{90} was estimated from gummed-film data to have occurred at Fargo following the Diablo Event of the Plumbbob series. The shot yield was 17 kt and there were approximately 1.8×10^8 μCi of Sr^{90} produced per kiloton of U^{235} fission. (The Sr^{90} estimate was originally made by assuming U^{235} fission.) These figures lead to the fractional wet deposition value of 3×10^{-12} m^{-2} as recorded in Fig. 1.

Table A-I Gummed-film network data for Tumber-Snapper and Upshot-Knothole series.

Sampling station	Cloud arrival time (H + hr)	Altitude of trajectory (ft)	Dry (D) or rain (R)	$\mu Ci/m^2$
		TUMBLER-SNAPPER SERIES		
		Shot Able 1 kt 793 ft air		
Salt Lake City, Utah	24	10,000	R	2.3
Rock Springs, Wyo.	30	10,000	R	0.5
Scottsbluff, Nebr.	42	16,000	R	1.8
Kansas (3 stations)	24	16,000	R	1.8
Colombia, Mo.	36	16,000	R	0.5
		Shot Charlie 31 kt 3500 ft air		
Flagstaff, Ariz.	48	24,000	R	0.9
Montgomery, Ala.	48	30,000	R	0.6
Southeast Coast	72	30,000	R	0.8
		Shot Easy 12 kt 300 ft tower		
Salt Lake City, Utah	6	all levels	D	16.5
Salt Lake City, Utah	6 to 12	all levels	R	40.0
Pocatello, Idaho	12	all levels	R	5.0
Rock Springs, Wyo.	12	all levels	R	7.5
Billings, Mont.	18	all levels	R	0.5
Rapid City, S. Dak.	24	all levels	R	5.0
Scottsbluff, Nebr.	24	all levels	R	2.5
		Shot Fox 11 kt 300 kt tower		
Grand Junction, Colo.	24	all levels	R	7.5
Goodland, Kans.	30	all levels	R	1.5
Scottsbluff, Nebr.	30	18,000 up	R	1.8
Des Moines, Iowa	36	18,000 up	R	3.0
St. Cloud, Minn.	48	18,000 up	R	1.2
		Shot George 15 kt 300 ft tower		
Pocatello, Idaho	24	10,000	D	7.0
Rapid City, S. Dak.	36	18,000	D	1.3
Tucson, Ariz.	36	?	D	2.5
Roswell, N. Mex.	36	?	D	2.5
Grand Junction, Colo.	36	?	D	1.0
Concordia, Kans.	48	?	D	3.0
Peoria, Ill.	42	24,000 up	R	5.0
Terra Haute, Ind.	48	24,000 up	R	7.5
Fort Wayne, Ind.	48	24,000 up	R	1.5
Grand Rapids, Mich.	48	24,000 up	R	6.0
Milwaukee, Wis.	48	24,000 up	R	5.0
Toledo, Ohio	48	24,000 up	R	1.5
Upper N. Y. and Pa.	60	24,000 up	R	1.5

Table A-I. Gummed-film network data for Tumbler-Snapper and Upshot-Knothole series (continued).

Sampling station	Cloud arrival time (H + hr)	Altitude of trajectory (ft)	Dry (D) or rain (R)	$\mu Ci/m^2$
		Shot How 14 kt 300 ft tower		
Boise, Idaho	24	all levels	R	30.0
Boise, Idaho	36	all levels	D	2.0
Pocatello, Idaho	24	all levels	D	2.5
Pocatello, Idaho	36	all levels	D	0.6
Rock Springs, Wyo.	24	all levels	D	0.6
Helena, Mont.	24	all levels	R	20.0
		UPSHOT-KNOTHOLE SERIES		
		Shot Annie 16 kt 300 ft tower		
Raton, N. Mex.	24	18,000 up	D	1.5
Raton, N. Mex.	30	18,000 up	D	1.0
Roswell, N. Mex.	30	18,000 up	D	0.8
Dallas, Tex.	36	18,000 up	D	5.0
Memphis, Tenn.	36	18,000 up	D	3.2
Knoxville, Tenn.	36	18,000 up	R	8.5
New York, N. Y.	48	18,000 up	R	5.0
Philadelphia, Pa.	48	18,000 up	R	2.5
		Shot Nancy 24 kt 300 ft tower		
Salt Lake City, Utah	18	18,000 up	D	75.0
Salt Lake City, Utah	39	18,000 up	D	5.0
Casper, Wyo.	18	18,000 up	D	10.0
Casper, Wyo.	30	18,000 up	D	1.5
Rapid City, S. Dak.	36	18,000 up	D	3.5
Willstop, N. Dak.	36	10,000 up	D	5.0
		Shot Ruth 0.2 kt 300 kt tower		
Phoenix, Ariz.	18	all levels	D	1.5
Las Vegas, Nev.	6	all levels	D	1.5
		Shot Dixie 11 kt 6000 ft air		
Raton, N. Mex.	24	?	R	0.5
Kansas (3 stations)	24	?	R	0.5
Boston, Mass.	36	?	R	25.0
Providence, R. I.	36	?	R	5.0
		Shot Ray 0.2 kt 100 ft tower		
Yuma, Ariz.	24	10,000	D	2.5
		Shot Badger 23 kt 300 ft tower		
Las Vegas, Nev.	12	all levels	D	5.0
Las Vegas, Nev.	30	all levels	D	2.5
Flagstaff, Ariz.	18	18,000 up	D	0.5
Albuquerque, N. Mex.	18	18,000 up	D	12.5
Albuquerque, N. Mex.	36	18,000 up	D	2.5

Table A-I. Gummed-film network data for Tumbler-Snapper and Upshot-Knothole series (continued).

Sampling station	Cloud arrival time (H + 24 hr)	Altitude of trajectory (ft)	Dry (D) or rain (R)	$\mu Ci/m^2$
		Shot Badger (cont)		
Abilene, Tex.	24	18,000 up	D	0.5
Port Arthur, Tex.	36	18,000 up	D	7.5
New Orleans, La.	42	18,000 up	D	3.0
		Shot Simon 43 kt 300 ft tower		
Salt Lake City, Utah	30	10,000	D	1.0
Rock Springs, Wyo.	36	10,000	D	0.5
Cheyenne, Wyo.	42	10,000	D	0.5
Flagstaff, Ariz.	18	18,000 up	D	20.0
Flagstaff, Ariz.	30	18,000 up	D	2.5
Grand Junction, Colo.	36	18,000 up	D	15.0
Grand Junction, Colo.	56	18,000 up	D	1.0
Albuquerque, N. Mex.	36	18,000 up	D	15.0
Roswell, N. Mex.	18	18,000 up	D	0.5
Roswell, N. Mex.	36	18,000 up	D	65.0
Roswell, N. Mex.	56	18,000 up	D	5.0
Amarillo, Tex.	42	18,000 up	D	5.0
Amarillo, Tex.	60	18,000 up	D	1.5
Dallas, Tex.	42	18,000 up	D	3.0
Dallas, Tex.	60	18,000 up	D	1.0
Wichita, Kans.	60	18,000 up	D	2.5
Concordia, Kans.	60	18,000 up	D	1.0
New Orleans, La.	60	18,000 up	D	1.0
Jackson, Miss.	72	18,000 up	D	1.0
Memphis, Tenn.	72	18,000 up	R	1.0
St. Louis, Mo.	80	18,000 up	R	0.5
Milwaukee, Wis.	80	18,000 up	R	0.5
Grand Rapids, Mich.	80	18,000 up	R	0.5
Albany, N. Y.	36	40,000	R	80.0
New Haven, Conn.	42	40,000	R	5.0
Caribou, Maine	56	40,000	R	1.3
		Shot Encore 27 kt 2500 ft air		
Williston, N. Dak.	24	30,000	R	5.0
Billings, Mont.	30	18,000	R	2.0
		Shot Harry 32 kt 300 ft tower		
Grand Junction, Colo.	18	18,000	R	55.0
Raton, N. Mex.	18	18,000 up	D	10.0
Albuquerque, N. Mex.	18	18,000 up	D	40.0
Albuquerque, N. Mex.	30	18,000 up	D	2.5
Roswell, N. Mex.	18	18,000 up	D	1.5
Amarillo, Tex.	18	18,000 up	D	8.0
Concordia, Kans.	30	18,000 up	R	5.5
Wichita, Kans.	36	18,000 up	R	2.5
Kansas City, Kans.	36	18,000 up	R	2.5
Des Moines, Iowa	42	18,000 up	R	7.5
Marquette, Mich.	42	18,000 up	R	5.0
Green Bay, Wis.	42	18,000 up	R	1.8

Table A-I. Gummed-film network data for Tumbler-Snapper and Upshot-Knothole series (continued).

Sampling station	Cloud arrival time (H + 24 hr)	Altitude of trajectory (ft)	Dry (D) or rain (R)	$\mu Ci/m^2$
		Shot Harry (cont)		
Milwaukee, Wis.	42	18,000 up	R	1.2
Minneapolis, Minn.	42	18,000 up	R	2.5
Pittsburg, Pa.	56	18,000 up	R	1.0

Table A-II. Gummed-film network data from Operation Teapot Series.

Sampling station	Cloud arrival time (H + hr)	Altitude of trajectory (ft)	Dry (D) or rain (R)	$\mu Ci/m^2$
	Shot Wasp 1 kt	762 ft air		
Yuma, Ariz.	24	?	D	9.4
	Shot Telsa 7 kt	300 ft tower		
Denver, Colo.	30	all levels	D	2.9
	Shot Turk 43 kt	500 ft tower		
Grand Junction, Colo.	30	18,000 up	D	10.2
Denver, Colo.	36	18,000 up	D	23.6
Goodland, Kans.	48	18,000 up	D	5.0
Concordia, Kans.	48	18,000 up	D	1.5
Scottsbluff, Nebr.	48	18,000 up	D	1.1
Chicago, Ill.	60	18,000 up	D	0.6
Cleveland, Ohio	60	18,000 up	D	1.7
Cleveland, Ohio	80	18,000 up	R	0.4
New York, N. Y.	60	18,000 up	R	1.1
	Shot Hornet 4 kt	300 ft tower		
Flagstaff, Ariz.	18	18,000	D	6.4
Roswell, N. Mex.	30	18,000	D	0.8
Jackson, Miss.	36	18,000	R	1.1
Ind., Ill., Wis., Mich.	60	30,000	R	0.5
	Shot Bee 8 kt	300 ft tower		
Dallas, Tex.	42	18,000	D	0.6
	Shot Apple I 14 kt and Shot Wasp Prime 3 kt	500 ft tower and 700 ft air		
Albuquerque, N. Mex.	18	18,000 up	D	1.2
Albuquerque, N. Mex.	30	18,000 up	D	0.3
Roswell, N. Mex.	18	18,000 up	D	1.4
Roswell, N. Mex.	30	18,000 up	D	0.8
Amarillo, Tex.	36	18,000 up	D	2.3
Las Vegas, Nev.	30	?	D	3.2
Grand Junction, Colo.	30	18,000 up	R	0.8
Pocatello, Idaho	18	10,000	R	5.8
	Shot Post 2 kt	300 ft tower		
Salt Lake City, Utah	12	10,000	R	5.3
Casper, Wyo.	18	10,000	R	1.6
Grand Junction, Colo.	18	14,000	R	2.3

Table A-II. Gummed-film network data from Operation Teapot Series (continued).

Sampling station	Cloud arrival time (H + hr)	Altitude of trajectory (ft)	Dry (D) or rain (R)	$\mu Ci/m^2$
	Shot Met 22 kt 400 ft tower			
Grand Junction, Colo.	24	all levels	D	11.2
Grand Junction, Colo.	48	all levels	D	2.9
Grand Junction, Colo.	72	all levels	R	0.8
Grand Junction, Colo.	96	all levels	R	0.6
Denver, Colo.	24	all levels	D	15.5
Denver, Colo.	48	all levels	D	3.2
Denver, Colo.	72	all levels	D	0.4
Goodland, Kans.	30	all levels	D	1.3
Wichita, Kans.	36	all levels	D	3.8
Concordia, Kans.	36	all levels	D	0.9
Scottsbluff, Nebr.	30	all levels	R	2.0
Huron, S. Dak.	60	10,000	R	0.5
Fargo, N. Dak.	60	10,000	R	0.8
Detroit, Mich.	36	30,000 up	R	3.6
Cleveland, Ohio	36	30,000 up	R	7.1
Buffalo, N. Y.	42	30,000 up	R	2.4
Buffalo, N. Y.	60	30,000 up	R	0.7
Rochester, N. Y.	60	30,000 up	R	2.0
New Haven, Conn.	60	30,000 up	R	0.8
Boston, Mass.	60	30,000 up	R	0.7
	Shot Apple II 29 ft 500 ft tower			
Salt Lake City, Utah	18	all levels	D	11.8
Salt Lake City, Utah	30	all levels	D	4.5
Cheyenne, Wyo.	18	all levels	D	6.5
Cheyenne, Wyo.	48	all levels	D	2.1
Cheyenne, Wyo.	72	all levels	D	0.3
Colorado Springs, Colo.	18	all levels	D	0.7
Colorado Springs, Colo.	48	all levels	D	7.7
Colorado Springs, Colo.	72	all levels	D	0.6
Denver, Colo.	48	all levels	D	4.7
Denver, Colo.	72	all levels	D	0.7
Pueblo, Colo.	48	all levels	D	5.2
Pueblo, Colo.	72	all levels	D	0.3
Goodland, Kans.	48	all levels	D	4.4
Goodland, Kans.	72	all levels	D	0.5
Goodland, Kans.	96	all levels	D	0.4
Green Bay, Wis.	48	all levels	R	1.2
Milwaukee, Wis.	48	all levels	R	0.9
Scottsbluff, Nebr.	96	all levels	R	0.8
Des Moines, Iowa	72	all levels	R	0.9
Des Moines, Iowa	96	all levels	R	0.4
St. Louis, Mo.	72	all levels	R	1.3
Louisville, Ky.	72	all levels	R	1.3
Chicago, Ill.	72	all levels	R	0.6
Flagstaff, Ariz.	24	?	D	3.4
Amarillo, Tex.	48	?	D	2.8
Amarillo, Tex.	72	?	D	1.5
Dallas, Tex.	72	?	R	1.7
Dallas, Tex.	96	?	R	0.3
Fort Smith, Ark.	72	?	R	2.7
New Orleans, La.	72	?	D	0.9

Table A-II. Gummed-film network data from Operation Teapot Series (continued).

Sampling station	Cloud arrival time (H + hr)	Altitude of trajectory (ft)	Dry (D) or rain (R)	$\mu Ci/m^2$
	Shot Apple II (cont.)			
Jackson, Miss.	72	?	D	0.4
Jackson, Miss.	96	?	D	0.3
Atlanta, Ga.	96	?	R	0.6
	Shot Zucchini 28 kt 500 ft tower			
Cheyenne, Wyo.	36	all levels	R	1.7
Cheyenne, Wyo.	60	all levels	R	0.5
Colorado Springs, Colo.	60	all levels	R	1.2
Denver, Colo.	60	all levels	R	0.4
Denver, Colo.	84	all levels	R	0.6
Roswell, N. Mex.	96	10,000	R	0.9
Amarillo, Tex.	96	40,000	R	3.3
Amarillo, Tex.	120	40,000	R	0.5
Dallas, Tex.	120	40,000	R	0.9
Fort Smith, Ark.	120	40,000	R	1.1
Fort Smith, Ark.	144	40,000	R	1.6
Memphis, Tenn.	144	40,000	R	0.4

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